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MORPHOLOGY AND DEVELOPMENT OF SELECTED BADLANDS IN SOUTHEAST SPAIN: IMPLICATIONS OF CLIMATIC CHANGE

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ABSTRACT

Four areas were selected to represent a range of processes characteristic of badland surfaces in southeast Spain: Petrer and Monnegre in Alicante, Vera and Tabernas in Almería. At Petrer, rilling and swelling processes produce a deeply cracked surface drained by a finely textured network of shallow rills. At Monnegre, piping and rilling are differentially developed on slopes ultimately controlled by basal incision. At Vera, aspect-controlled lichen and vegetation cover produce a sequence of badland development within which the relative importance of piping, mass movement and rilling varies through the sequence. At Tabernas, simple overland flow is the dominant process, but aspect influences rill network density and badland evolution.

The factors controlling badland development can be grouped into those related to gross morphology, to surface cover and runoff generation, and to material properties. These factors are effective over varying timescales, implying that morphological response times differ among the selected badlands.

KEY WORDS badlands; southeast Spain; climatic change; rilling; pipes

INTRODUCTION

Badlands are characteristic forms in semiarid regions in which very rapid rates of erosion occur, and in many cases their development is the result of disturbances by man of a fragile natural equilibrium (Bryan and Yair, 1982). On many badland surfaces more than one process may operate and it is often the interaction between the processes (rilling, mass-wasting, piping and overland flow) that is a major factor in determining the evolution of badland slopes. Climatic change may alter the relationships between processes and modify the rates of erosion. The morphological response could be either an acceleration of erosion rates or a trend towards stabilization of badland surfaces.

This paper examines the morphology and temporal development of four selected badland sites in southeast Spain, paying special attention to the interaction between processes. The study includes two timescales: a short one, that examines seasonal variations over a one-year period, and a longer timescale, *that examines* changes over a ten-year period.

Four badland areas were studied: Tabernas and Vera, in Almería province, already studied by Harvey (1982), where we have monitored surface changes over the longer period; and Petrer and Monnegre, in Alicante province, where we have examined seasonal changes in the short term. From Monnegre we also have some information dating back to 1982.

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SITE CHARACTERISTICS

The Tabernas badlands are among the most extensive badland areas in Spain. They are cut in Upper Miocene (Tortonian) mudstones of relatively deep-water marine origin. They have up to *c.* 150 m vertical extent and have been developed over much of the Quaternary during sustained, tectonically induced dissection (Harvey, 1987). The study area appears to represent typical badlands developed entirely by overland flow and shallow mudslides (Harvey, 1982). On south-facing slopes, rill networks are clear and especially well developed on the steepest slopes on the gully heads.

The Vera badlands, cut in Upper Miocene (Messinian) gypsiferous marls, occur on steep slopes developed between Quaternary pediments and have a restricted vertical extent with a maximum local relief of up to *c.* 60 m. They are relatively young and have only developed since the dissection of one of the younger surfaces of the Vera basin (Harvey, 1987). On these slopes there is a full range of erosional forms from shallow discontinuous gullies to deep linear gullies. Bare surfaces on south-facing slopes, are rilled and there is local evidence of mudsliding (Harvey, 1982). North-facing slopes have a denser vegetation cover and a thin and resistant lichen crust. Deep and shallow piping, related to gypsum layers and veins in the rock, is also important in relation to rill generation.

Present climatic conditions are very similar in both areas. Using data from Elias and Ruiz (1977) the mean annual precipitation ranges from 245 to 268 mm for Tabernas and Vera respectively, although Geiger (1970) estimates rather lower totals (<200 mm in each case). Mean annual temperatures are 18°C. The average number of rain days ranges from 43 in Tabernas to 33 in Vera.

Mineralogical analysis of clays from Tabernas and Vera (J. Petch, pers. comm.) shows the main difference to be that the Vera marls are rich in smectite and gypsum. This would be likely to increase the potential for swelling and slaking, increase infiltration capacity and enhance their erodibility (Alexander and Calvo, 1990).

The Petrer badlands are developed on Upper Cretaceous (Senonian) marls. They have a maximum local relief of *c.* 80 m. The presence of badland slopes is related to the dissection of Pleistocene valley fills strongly linked to diapiric uplift along an E–W axis near the southern margin of the Prebetic ranges. Surface processes are dominated by rilling, swelling and cracking and the development of shallow bridge piping. Shallow slips are a secondary process.

The Monnegre badlands are also developed on Senonian marls and have a maximum local relief of *c.* 100 m, also related to diapiric activity. Deep piping and rilling are the dominant processes, related to a base-level control by the main gully system. Detailed morphology shows great spatial variation related to lithology and structure.

Climatic conditions at Monovar (near Petrer) and Alicante (near Monnegre) show a mean annual precipitation ranging from 296 to 339 mm, again with Geiger (1970) estimating a little less, just below 300 mm for both locations. Mean annual temperatures are 14 and 18°C and the average number of rain days ranges from 33 in Monovar to 88 in Alicante.

RESULTS

The method used is based on sequential photography of selected sites or plots from fixed points. At Tabernas (Figure 1) we have monitored the whole of a large south-facing slope on eight occasions between 1980 and 1988. At Vera (Figure 1) we have monitored two south-facing slopes on seven and nine occasions respectively between 1978 and 1988. At both Petrer and Monnegre we have information from eight study plots, recorded on eight occasions over 14 months in 1987 and 1988. In addition we have a photographic survey of the Monnegre site, taken in 1982.

The sequential photographs were analysed, in a manner not unlike that used by Suwa and Okuda (1988), to derive a series of indices to represent temporal variations in surface properties, including properties relating to the rill networks, pipes, crack patterns, surface roughness and mass movements. For example, for rills the network on each photograph has been assigned an index value on an arbitrary scale (0–10) to express the degree of development based on network density, bifurcation and continuity. Each set of photographs was

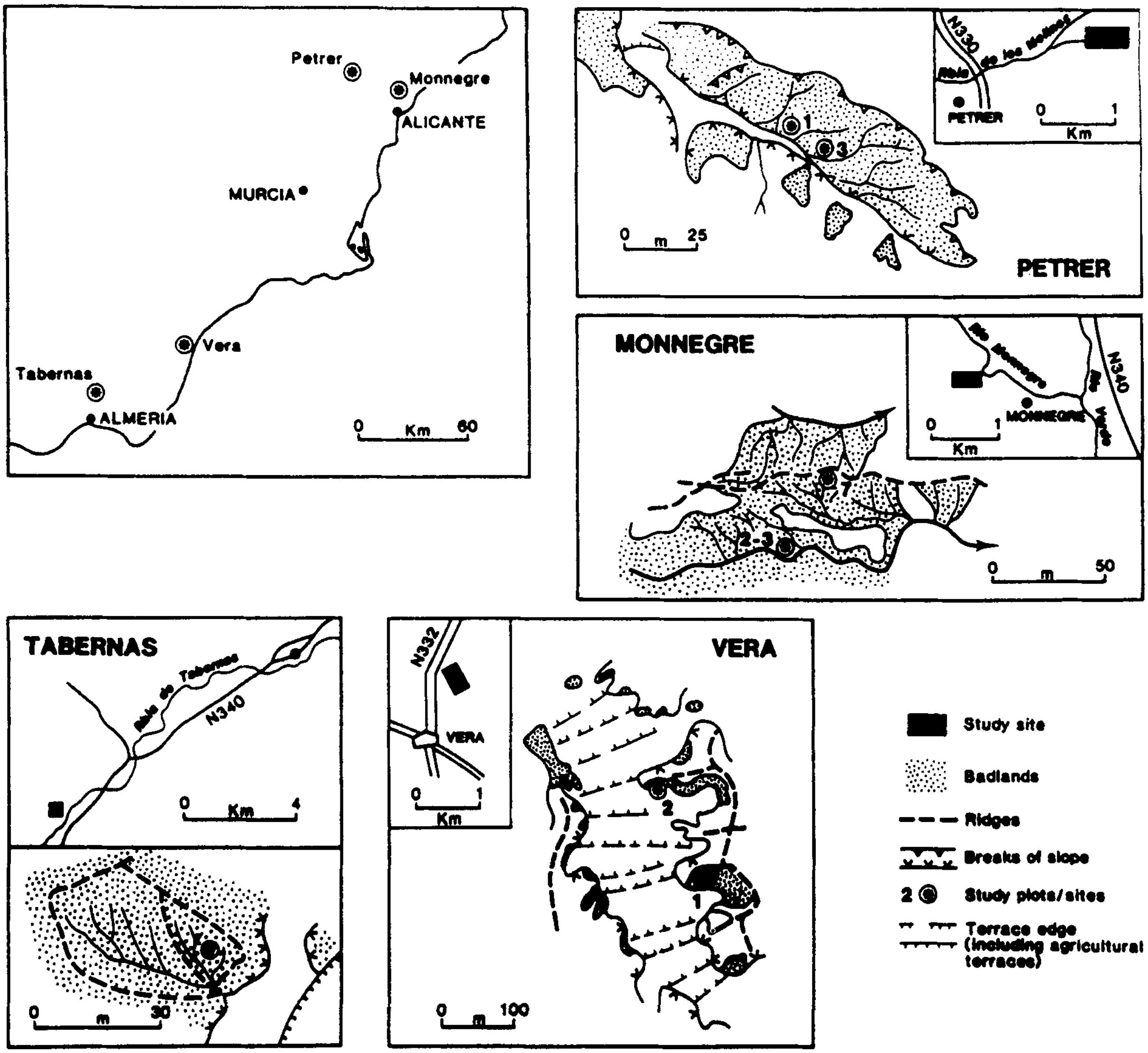

Figure 1. Location of study sites

cross-checked to ensure internal standardization, then each set was checked against those for the other plots/sites and scaled, where necessary, to achieve consistency throughout the data. For each index, low values relate to weak development of the particular property.

At Tabernas, the analyses of the eight morphological sequences (Figure 2) show very low temporal variations in all the variables studied. Rill network development, represented in Figure 3 for the beginning and the end of the study period, shows very little net change, consisting only of the disappearance of some tributary rills and the formation of other new ones. The response of the rill sequence to rainfall (Figure 2) shows only small fluctuations of rill index over the period. The low rate of swelling is evidenced by the few changes in crack density, surface roughness and extent of the rough areas (Figure 2). Despite the low rates of morphological change, erosion rates are high, as demonstrated by the temporal changes in the accumulation of sediments on the main gully bottoms and on the pediment surfaces below the gullies.

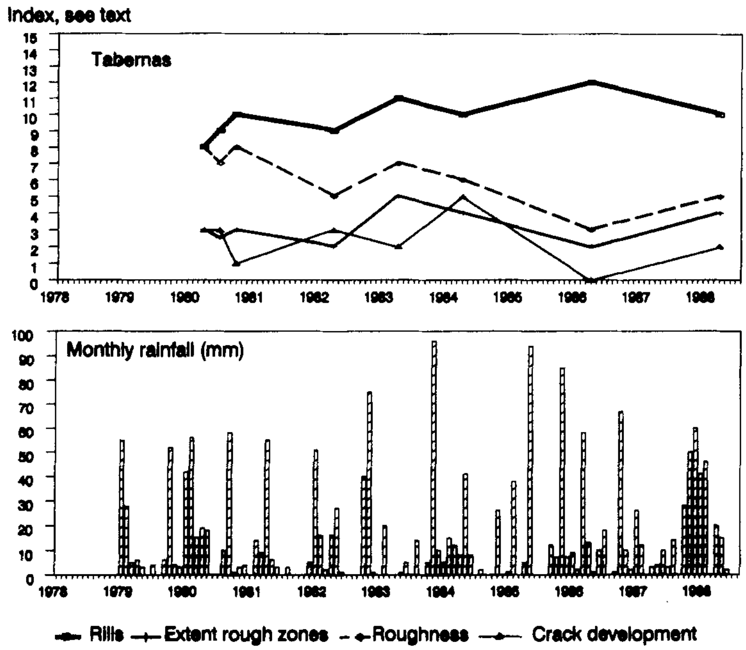

Figure 2. Rainfall and morphological change at Tabernas badlands

At Vera, by contrast, we observed two complete sequences of destruction and regeneration of the rill network. These two sequences (Figure 4) are completely recorded for Vera site 1, but only the first on Vera site 2, because of a gap in the data. Although the numerical indices of morphological change used in Figure 4 do not permit statistical analysis, some very clear trends are evident. Rill generation seems to be linked with the

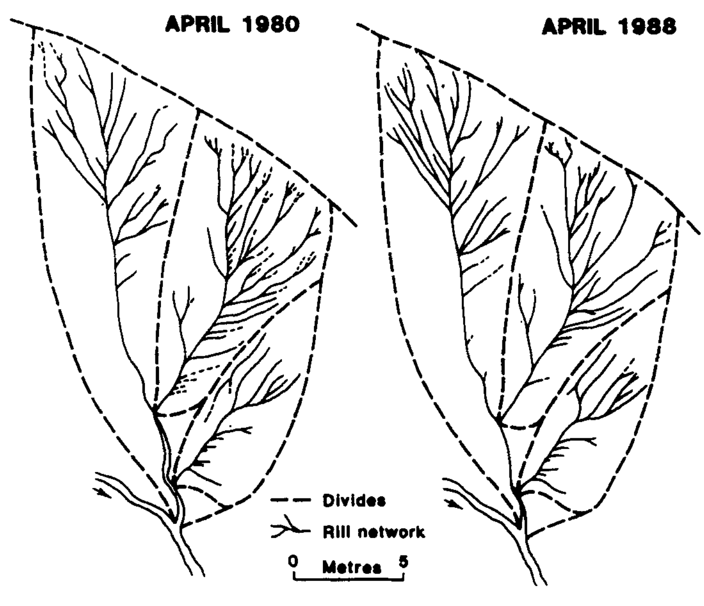

Figure 3. Tabernas rill networks at beginning and end of study period

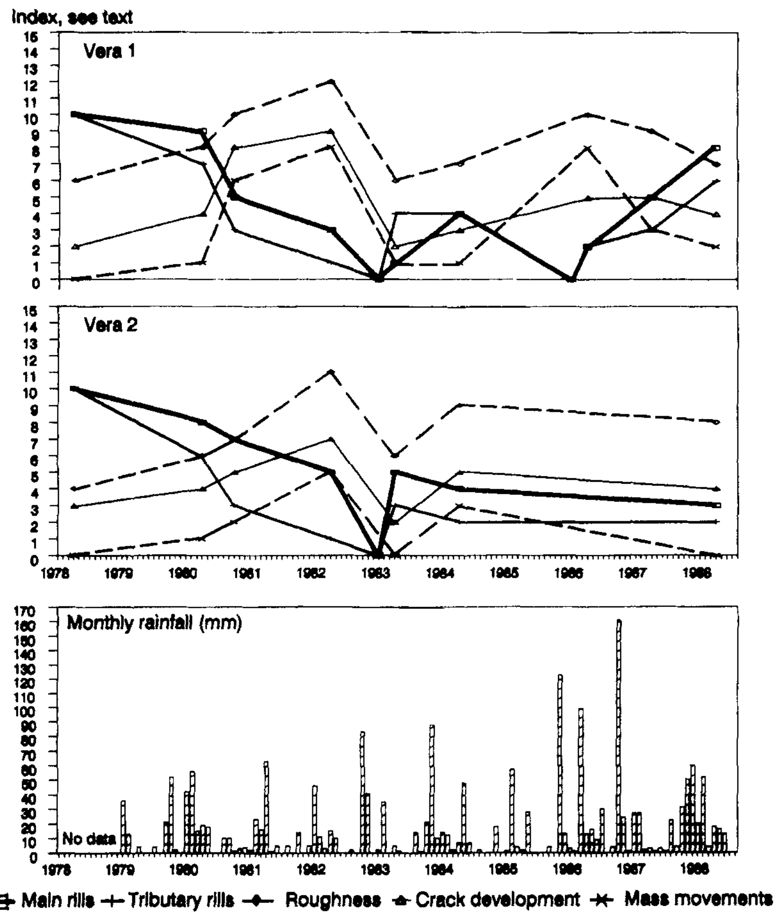

Figure 4. Rainfall and morphological change at Vera badlands

more humid period that starts in 1986 and rill destruction with drier periods. Together with climatic characteristics, intrinsic geomorphological factors also seem to be responsible for the morphological changes. Therefore, a developed rill network produces instability in the inter-rill areas. This can produce slow mass movements, as a consequence of swelling, that close the tributary rills and increase the surface roughness (Figures 4 and 5, from 1980 to 1982). After that, during a drier period with some storms, there were failures and the removal of regolith cover. In 1983 and 1984 some increase in rill density occurred and surface roughness increased in a period with moderate rains and presumably changing soil moisture content. Heavy rains in 1985–86 produced mudflows that removed surface material and filled up the main rill bottoms. Subsequent rains (October 1986) started to generate new tributary rills and complete the sequence of morphological change.

At Petrer, plots 1 and 3 (Figure 6) are representative of the range of morphological situations, reflected especially by regolith thickness, which is deeper in Petrer 1. The available data for a 14 month period show short-term, partly seasonal variations and, therefore, suggest an immediate response to rainfall conditions. From the range of variables recorded at Petrer there are some, related to rills and pipes, that may progressively change over a longer timescale, and others, related to surface properties, e.g. crack characteristics, that reflect very short-term fluctuations in soil moisture. The most significant changes are those affecting surface roughness and tributary rill development. Roughness (Figures 6 and 7) is low during the winter months (from October to January) when the regolith remains moist. Tributary rills show high densities, as a consequence of the heavy rains and high moisture retention during winter rains. In contrast,

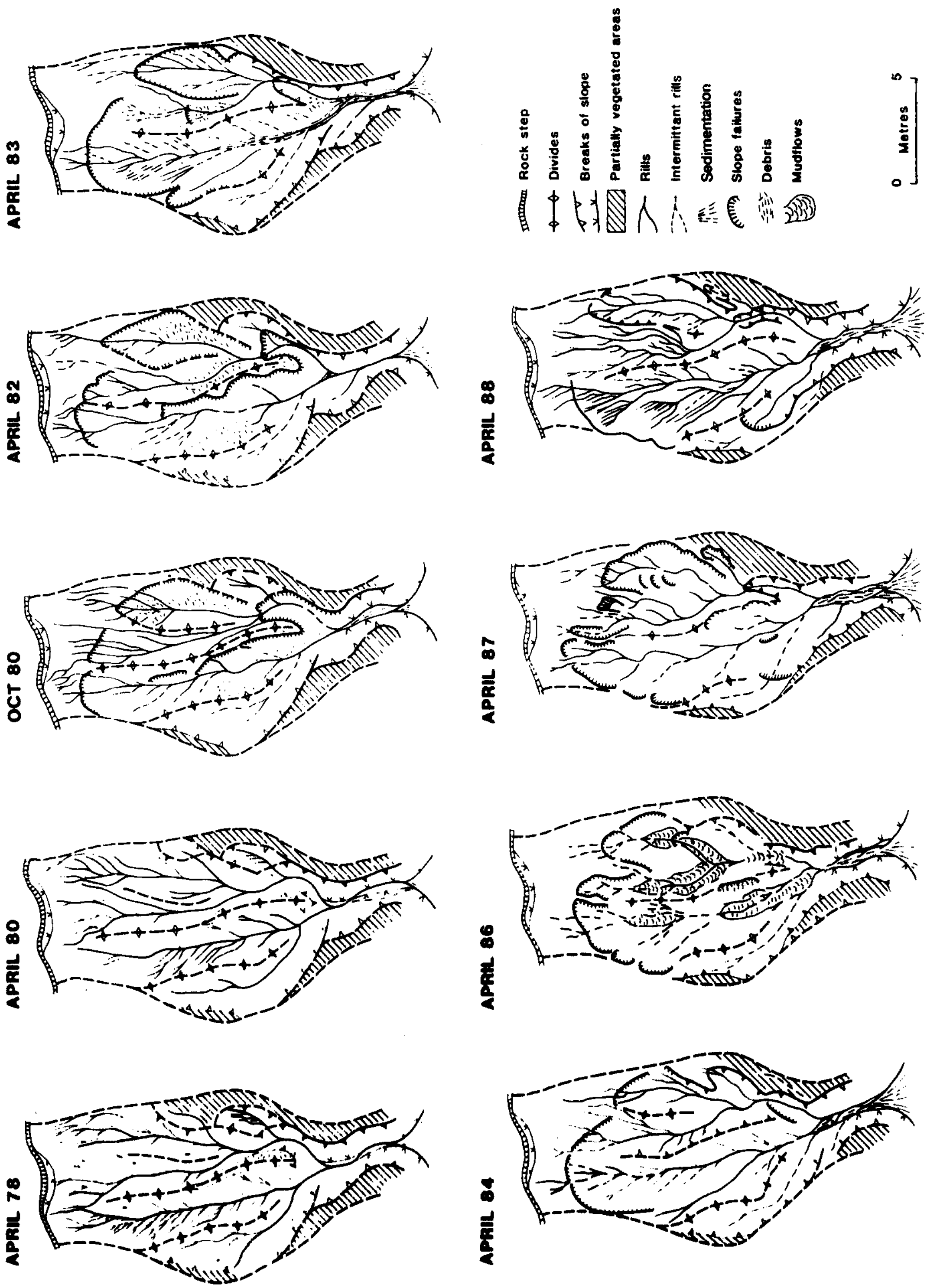

Figure 5. Sequence of morphological change at Vera 1

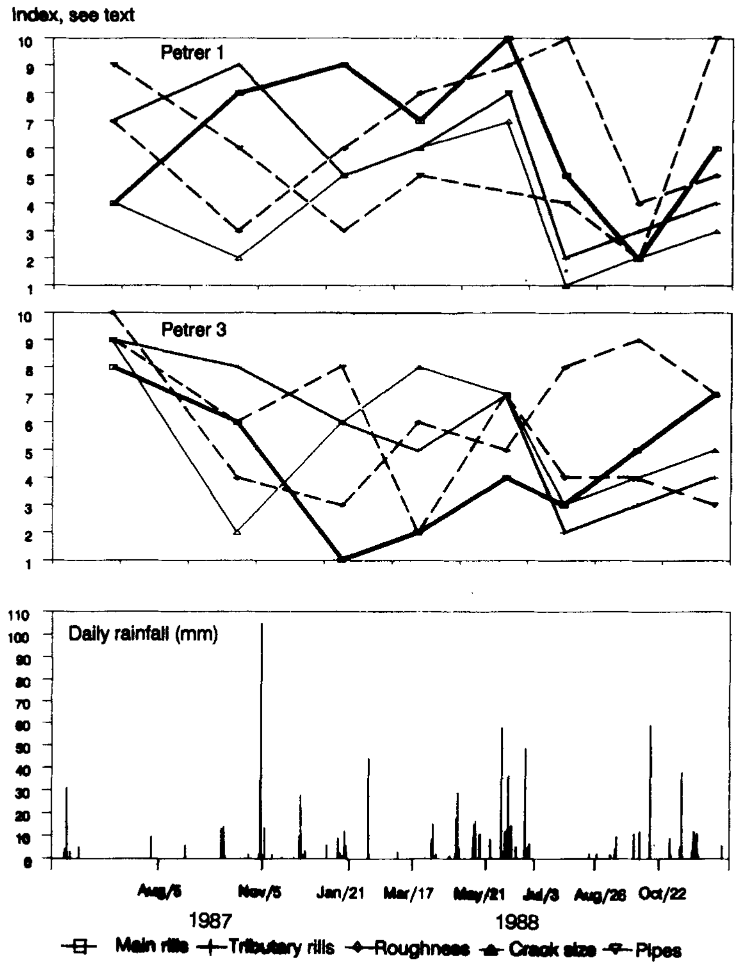

Figure 6. Rainfall and morphological change at Petrer badlands

roughness values increased during the warmer months. During this period there were only occasional rains, and strong contrasts in soil moisture with subsequent swelling and contraction behaviour.

At Monnegre the characteristics of the eight studied plots are reflected by the contrasted behaviour of plots 2–3 and 7 (Figure 8). Monnegre 2–3 is on a low gradient slope, with vertical pipes related to tension cracks and a thin regolith cover. The clarity and development of the rills varies inversely with the pipe index, as the pipe inlets open. Surface roughness behaviour shows a similar temporal change, but on this plot it is more closely related to erosional pinnacles and splash processes than to swelling. Monnegre 7 (Figure 9) represents conditions on steep slopes with rills and rill-pipes and a deeper regolith. The rhythm of morphological change is opposite to that in the other plot and more like that observed at Petrer. Rills and pipes are well developed during the winter but are destroyed or reduced during the summer months by the higher swelling rates, causing increases in surface roughness. In both cases, Monnegre 2–3 and 7, the development of rills is related to the development of pipes, primarily because of the base-level control exerted by pipes on the system as a whole.

Despite these short-term changes, longer-term information, also available from Monnegre, suggests only a slow rate of progressive rill development. The main change noticed between 1982 and 1989 was that previously planar inter-rill areas became more convex. Downcutting on the main gullies seems to be the most important factor controlling the evolution of these badlands.

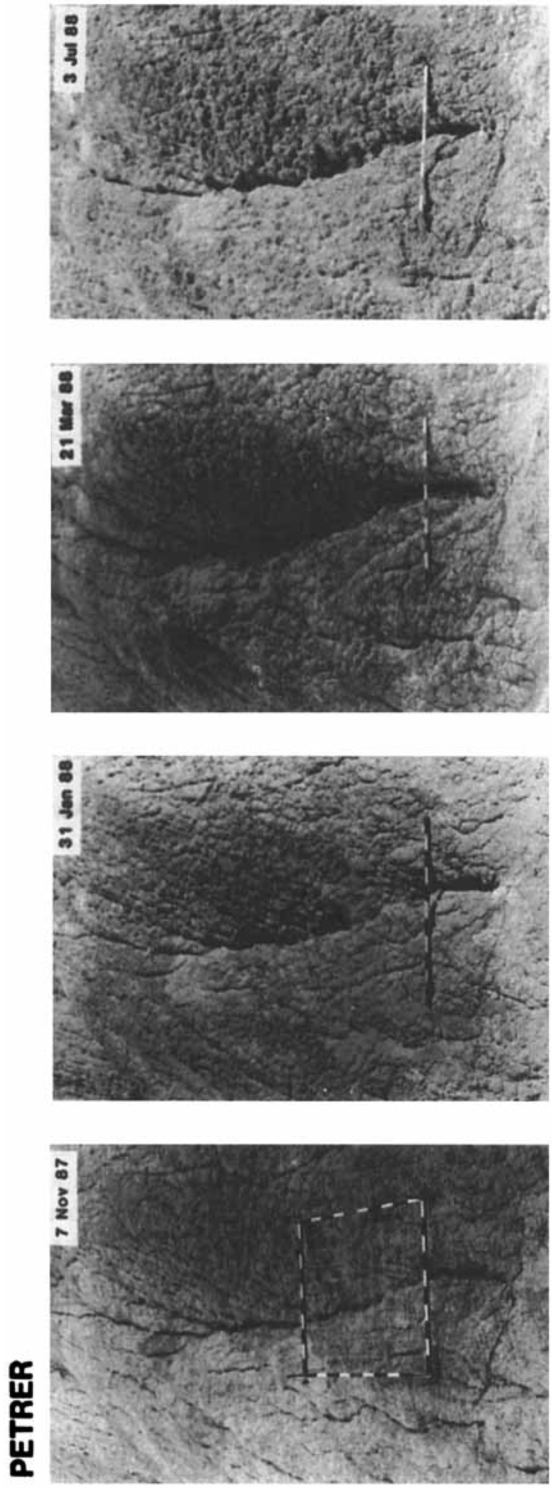

Figure 7. Selected sequence of morphological change at Petrer 1

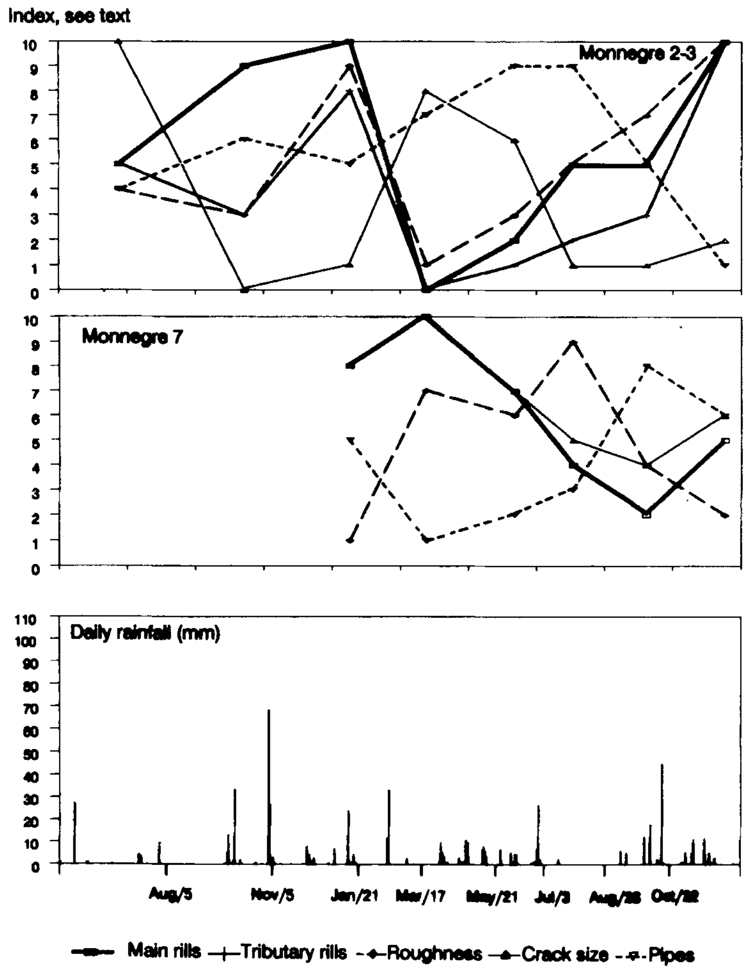

Figure 8. Rainfall and morphological change at Monnegre badlands

DISCUSSION AND IMPLICATIONS

Our results allow us to remark first on the influence of material properties, especially mineral composition, on badland morphological development. There is a strong contrast between Tabernas and Vera in the geomorphological response and process interactions in the long and short term. We think that these differences are due to material contrasts between the two sites, especially the high gypsum content of the Vera marls. A second controlling factor is the surface form, which appears to be more important at Vera, where on a very dynamic surface there is a succession of rill development followed by removal of surface material by mass movements, then by the initiation of a new rill system. At Monnegre, basal downcutting controls rill and pipe progression.

Climatic conditions at Vera work as a trigger for specific processes: dry periods with low-frequency heavy rains cause rill destruction, leading to more uniform percolation of water (as described by Imeson and Verstraten, 1988) favouring mass movement, while more frequent rains favour rill development.

In the short term, material properties and rainfall/drought sequences seem to be the most important factors. For material properties, a high capacity for swelling is characteristic in Petrer 1 and Monnegre 7. This affects the tributary rill network and surface roughness, and is directly related to the frequency of wet/dry cycles, which are important during the summer months.

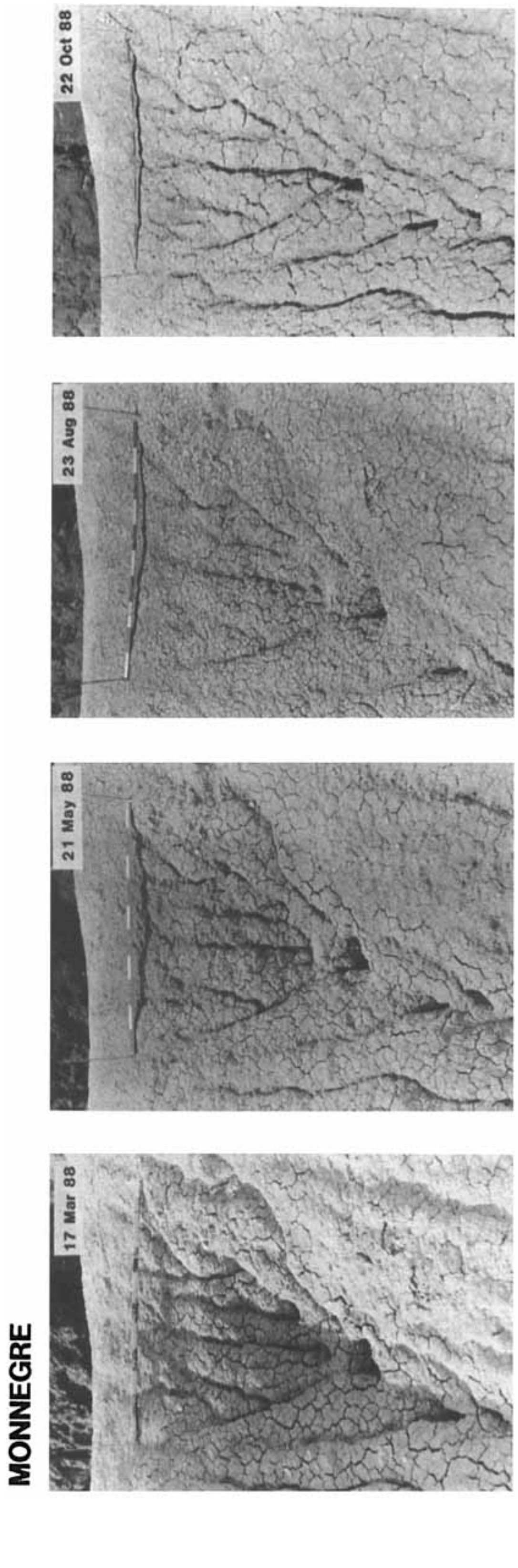

Figure 9. Selected sequence of morphological change at Monnegre 7

As at Tabernas, Petrer 3 and especially Monnegre 2–3, sites with only a thin regolith cover and a compact surface, show few morphological changes. This is due to the dominance of only one or two processes—rilling in Tabernas, rilling and piping in Petrer 3 and Monnegre 2–3—rather than to more complex process interactions.

At several of the study sites, badland evolution is controlled by interactions between rilling and a group of processes that depend on mass properties and therefore on weathering rates. Although the style of the interaction (i.e. the relative importance of rilling) is controlled by material properties, current morphological sequences reflect current climatic conditions. If climate were to change, especially the frequency of heavy rains or the duration of, and moisture availability during, the intervening periods, then the relative importance of different processes and the style of the morphological response would also change. Not all sites would respond in the same way. An increase in rainfall frequency would increase the effectiveness of rilling, reinforcing its dominance at Tabernas, its coupling with piping at Petrer 3 and Monnegre 2–3, and perhaps convert those sites now characterized by complex process interactions (Vera, Petrer 1 and Monnegre 7) to dominance by rilling. Conversely, a decrease in rainfall frequency would reduce the effectiveness of rilling and increase the effectiveness of cracking and desiccation-related processes, perhaps increasing the complexity of process interactions in what are currently simple situations.

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